Investigating Energy Savings Within Residences Using Smart Home Systems

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Abstract

This project investigates energy and operational cost savings achievable for residences using smart home systems (SHS) for climate control. Energy consumption and cost analysis are performed using an in-house HVAC model created using Microsoft Excel, based on a chosen floor plan and a series of design assumptions and criteria in accordance with Australian building codes and standards. Energy consumption is calculated as the heating or cooling load for each room and subsequently the overall household, capturing the year-round climate control capabilities of the iZone SHS across summer and winter seasons in Perth on an hourly basis. The heating and cooling loads are performed and compared for a traditional system (running 24-hour and 18-hour) and SHS (18-hour). The model considers heat transfer via conduction through building materials used for house construction, and solar radiation gain components for glass building materials. The electrical climate control components modelled include air conditioning, LED downlighting and roller blinds. The model also determines carbon emissions for each scenario. Results indicate potential savings of 50 – 60% and over 65% reduction in CO2 emissions. The model results were successfully validated using commercial HVAC software CAMEL+.

1. Introduction

The attainment of thermal comfort in the home is becoming increasingly difficult due to the rising costs of living and utilities required to provide this comfort. There is a general understanding that smart home systems can aid in the pursuit of comfortable living conditions, reducing costs and carbon emissions, but there has been limited work in the Australian climate to assign a ‘dollar value’ that quantifies the financial and environmental savings achievable. Both areas are crucial drawcards when smart home system manufacturers are marketing their products and services to clients.

In this project, we seek to objectively quantify the energy (and consequently cost) savings households can achieve by implementing the iZone SHS, which integrates electrical household applications used for climate control into a centralised network, including air conditioning, LED downlighting and electric roller blinds. The energy consumption is compared to the operational costs for households without such technology. We have also investigated how the carbon footprint could be reduced through energy savings achieved through SHS implementation l. In addition to marketing their goods and services to existing homeowners, the outcomes of this project may enable the client to diversify their customer portfolio, by collaborating with both residential and commercial building companies who could incorporate the smart home technology into their building and construction packages. Since the majority of the client's profit is generated in the eastern states of Australia, this project has the potential to grow the customer base and increase turnover in Western Australia, increasing yield for the client nationwide.

2. Process

A modelling approach was taken which aligns with the method used by the HVAC industry. An in-house model was developed using Microsoft Excel to determine the heating and cooling loads depending on the season based on a given house schematic. Different scenarios for the chosen house configuration are simulated and resulting energy consumption is compared with and without the iZone SHS implementation. The iZone SHS in the model is centred on household equipment and devices that are used for climate control, with the major component being the air conditioning system. Different temperature datasets are used, including data from various Bureau of Meteorology weather stations around Perth, to identify any patterns in energy consumption based on residential location within the Perth metropolitan region. Validation of the in-house model is performed by modelling the same house configuration using a commercially available HVAC software, CAMEL+ by Australian software developer ACADS-BSG.

The model to determine the heating and cooling loads was created based on a floorplan chosen from a Perth-based home building company. A standard 4-bedroom, 2-bathroom single storey home was chosen. Using the dimensions provided in the floorplan, the 2D dimensions of each of the rooms are calculated, which yielded an overall internal floor area of approximately 100m^2. Assumptions for the materials and dimensions of walls, windows, roof pitch and door widths were established based on the standards defined for residential buildings in the Australian national construction codes (NCC) to create a three-dimensional analysis of the house structure.

2.1 Modelling Equations

The house is divided into its main structural components (i.e., walls, floor, roof, windows, doors), and heat transfer calculations are performed considering the thermal properties of materials in each structural component. The model focuses on heat gains and losses via transmission, or conduction and convection, and solar radiation applied to the windows and glass doors of the house. To calculate heat transfer due to conduction, the Cooling Load Temperature Difference (CLTD) method is used in the following equation:

$$Q_{transmission} = U \times A \times \Delta T \qquad [1]$$

Where:

- **Q** is the rate of heat transferred in watts [W]
- **U** is the heat transfer coefficient for the material experiencing the heat transfer, measured in W/m^2. This is empirically determined.
- **A** is the area of the material where the heat transfer is occurring in m^2
- **ΔT** is the temperature differential that is ultimately the driving force of the heat transfer phenomenon. In this study ΔT is taken as difference between the outdoor temperature and the indoor temperature, which we have defined as a setpoint of 23°C.

CLTD for transmission loads is applied to all structural components of the house and is calculated per room and in each cardinal direction (north, south, east, west). It is important to note that ΔT is positive in the summer and negative in winter (resulting in a negative Q value in winter, implying heating is to be supplied rather than cooling).

The windows and glass sliding doors of the house also experience heat gain via solar radiation. Solar radiation heat transfer is expressed using the following equation:

$$Q_{solar} = SHGC \times R \times A \qquad [2]$$

Where:

- SHGC is the Solar Heat Gain Coefficient. This represents the percentage of solar radiation admitted through a glass surface. Being a fraction the SHGC is always between 0 and 1.
- R is the solar radiation in W/m^2
- A is the area of the glass door or window in m^2

The total heat transfer for a glass component of the house at any given time is:

$$Q_{total} = Q_{transmission} + Q_{solar} \qquad [3]$$

2.2 Solar Radiation Modelling

Solar radiation data was obtained from the National Solar Radiation Database (NSRDB), which is managed by the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy. The NSRDB includes three fundamental measurements of solar radiation: global horizontal irradiance (GHI), direct normal irradiance, and diffuse horizontal irradiance, plus meteorological data from worldwide locations. The model uses hourly GHI values from the database over 5 years from 2015 – 2020. The model determines the GHI distribution throughout the day in each cardinal direction using the solar azimuth angles (the angle between the projection of the sun's centre onto the horizontal plane and the due north direction). The azimuth angles were averaged across each month on an hourly basis and converted into bearings using manipulation in Excel. This results in the distribution of GHI with respect to direction, which allows the model to visualise how the solar radiation varies throughout the day on each face of the house.

2.3 Temperature Data Modelling

The model was run using two main categories for its temperature dataset:

1. Hourly temperature data averaged over 5 years for Perth, obtained from the (NSRDB).
2. Hourly temperature data for a single year between 2015 – 2022 for multiple weather stations around Perth suburbs, obtained from the Bureau of Meteorology (BOM). The data was purchased from the BOM, with the intention to locate key weather stations that would truly encapsulate an accurate cross-sectional representation of the Perth metropolitan area. These include coastal (western), central, inland eastern hills, northern and southern suburbs.

2.4 Residential CO_2 Emissions

The average household rate of CO_2 emissions per unit electricity consumed is based on the 'scope 2 emission factor' for the Australian State or Territory in which the consumption occurs (National Greenhouse Accounts Factors, 2021). It is defined with respect to energy sent out on the grid to ensure that end users of electricity are only allocated the CO_2 emissions for the electricity they purchase and consume, instead of emissions attributable to electricity lost in transmission and distribution (National Greenhouse Accounts Factors, 2021). In Western Australia, the scope 2 CO_2 emissions rate is 0.67 kg CO_2/kWh (National Greenhouse Accounts

Factors, 2021). This rate can be used to determine and thus compare the CO_2 emissions for both traditional system and SHS simulations according to the equation:

$$CO_2\ Emissions\ [tonne] = Q[kWh] \times EF\ [kg\ CO2/kWh]/1000 \qquad [4]$$

Where:

- **CO_2 Emissions** is the amount of CO_2 emissions in tonnes
- **Q** is the quantity of electricity purchased in kWh
- **EF** is the scope 2 CO_2 emissions factor for the Australian State or Territory in kg CO2/ kWh

2.5 Traditional and SHS Model Setup

Traditional Model

The model is configured to run the air conditioning for all rooms throughout the day to maintain the setpoint temperature. Traditional systems have no capacity to remotely turn on/off the system or create an automated schedule, therefore the system operates 24 hours to achieve the desired level of comfort. The traditional system's hourly cooling/heating load is determined without any operating schedule or implementation of internal smart components such as roller blinds. In the worst-case scenario, all LED downlights are left on. The traditional model was further modified to run for the same duration (18 hours) and timings as the SHS schedule. This create a more realistic scenario of occupants manually turning off the air conditioning system when leaving the house and manually turning it back on again when arriving home. All rooms are turned on and off at the same time when triggered (i.e., no capacity to activate/deactivate particular zones of the house).

SHS Model

The key difference between a traditional system and the SHS is the potential for s for remote access to and control of the home's climate control system. The user can specify different setpoint temperatures in each room or zone and configure a set of rules and schedules for the air conditioning and other climate control/electrical components that are connected in the smart home ecosystem. Smart roller blinds and smart LED downlights are modelled. The SHS scenario is modelled based on a defined occupancy schedule throughout the day for a family of two working adults and three school-aged children. A standard setpoint temperature of 23°C is fixed across all rooms and zones. Cooling/heating is performed for 18 hours per day and is scheduled to turn off when all members are away from home in the middle of the day.

3. Results and Discussion

The average daily heating and cooling loads in kWh/day for each simulation are compared in the figure below. The results indicate higher heating demands in the winter months than the cooling demands required in the summer months, with zero cooling requirements from June – September, for all three traditional and SHS simulations. Conversely, a certain extent of heating is required across all months in both simulations. The comparison indicates significantly lower heating and cooling demands by the SHS than the traditional systems overall, which experienced higher variance/extremities and irregularities compared to SHS consumption curves that are more consistent throughout the year. The traditional (18 hour) results display a slightly higher maximum heating requirement on average than the traditional (24 hour) results. While the traditional (18 hour) running costs were marginally lower than the traditional 24-hour running costs, the SHS energy consumption and costs were found to be significantly lower than that of the traditional systems. The average cost per day for heating and cooling combined was (in AUD) \$17.26, \$13.06 and \$6.15 for the traditional, traditional (18 hour) and SHS simulations respectively. The combined annual cost was \$6300, \$4766 and \$2246 for the traditional, traditional (18 hour) and SHS simulations respectively. The lower SHS costs yields a 64% cost reduction from the traditional system and a

53% cost reduction from the traditional (18 hour) system. The average annual CO_2 emissions was 21, 14 and 6.7 tonnes for the traditional, traditional (18 hour) and SHS simulations respectively. The SHS implementation represents a 68% reduction in CO_2 emissions from the traditional system and a 53% reduction in CO_2 emissions from the traditional (18 hour) system.

The accuracy of the model was validated using CAMEL+ HVAC software for the same household configuration with a traditional system as a sanity check to ensure the in-house model results were reasonable. The results from the CAMEL+ software indicate that while the load results for each room were determined to be higher than the in-house model, the results of the in-house model overall are deemed to be reasonable and accurate. Overall, the results of the simulations validate the hypothesis that employing iZone SHS for climate control decreases household energy consumption and achieves considerable cost savings compared to the traditional system. From an environmental perspective, SHS can enable households to reduce CO_2 emissions. The results overall are reasonable with respect to the defined model parameters and align sensibly with results, statistics and industrial heuristics from other studies noted in the literature. However, the caveats of the model configuration may imply that realistically, the SHS may not yield energy cost savings to such a high extent as per the simulation, thus the gap between SHS and traditional systems would be smaller. The lack of a temperature differential tolerance threshold also contributes to the increased load requirements in both traditional and SHS simulations. Even minor deviation between outdoor and indoor temperature results in a load requirement. While this load is minimal due to a low ΔT, it still increases the overall energy usage especially when results are scaled up to the annual energy consumption. The results also show that cooling requirements were overall lower than the heating requirements, where heating demand was present all year round, cooling was not required in 4 months of the year. Looking at the BOM temperature data, cost and energy consumption patterns emerged when comparing results between the different weather stations. It was found that the weather stations located on or towards the Perth coastline achieved lower energy consumption and operating costs compared to the eastern weather stations further away from the ocean. This is due to the cooling south-westerly sea breeze that occurs in the late afternoons, which would have the greatest cooling impact on the coastal areas in reducing these house's cooling loads in the summer. Conversely, the inland suburbs experience extended effects of the hot, dry easterly breeze that would ultimately place a higher cooling load.

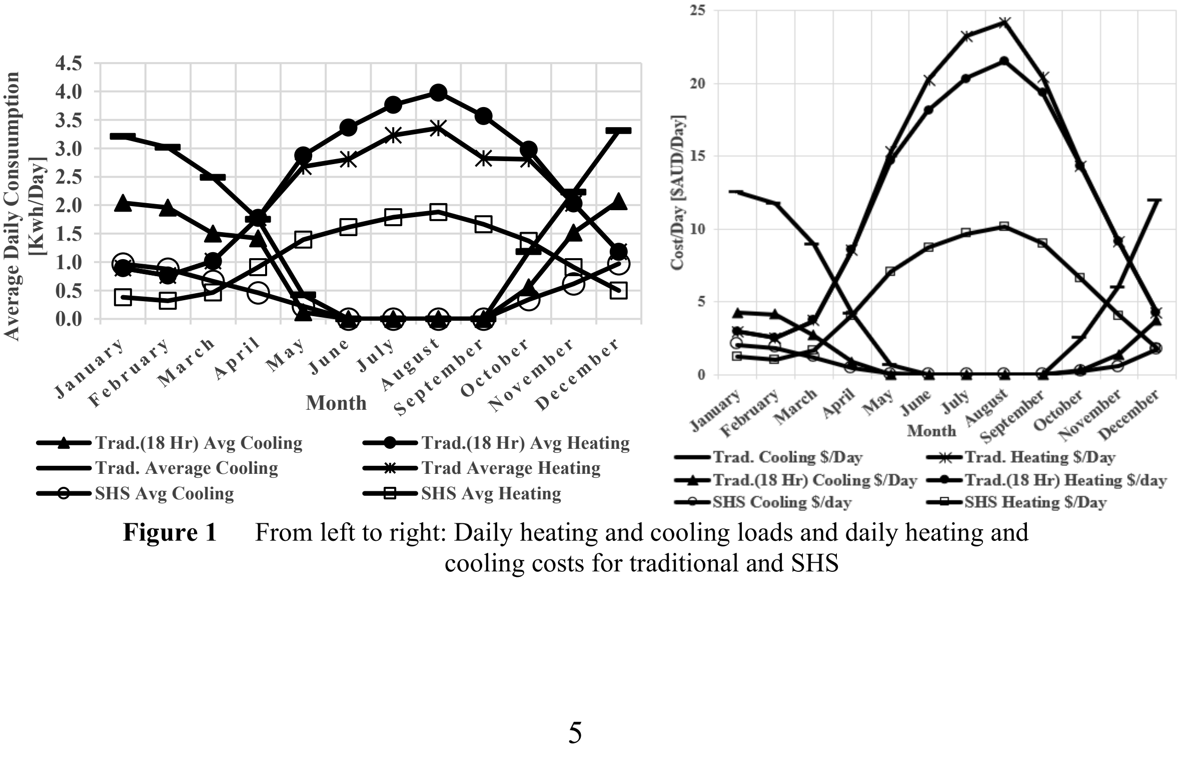

Figure 1 From left to right: Daily heating and cooling loads and daily heating and cooling costs for traditional and SHS

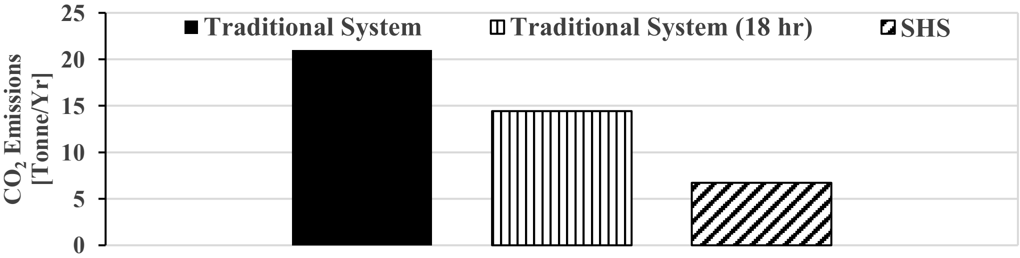

Figure 2 Average annual CO2 emissions for traditional and SHS

4. Conclusions and Future Work

The iZone SHS for climate control in Perth was objectively modelled for a specific floor plan under several assumptions. The SHS was found to achieve meaningful energy and operational cost savings when compared to those of a traditional system. Air conditioning heating and cooling loads, smart roller blinds and smart LED downlights were modelled. Reduced energy consumption yielded lower CO_2 emissions which provides further marketable value for the client. Additional temperature data from the BOM was modelled, and the model was validated using CAMEL+ HVAC software. Savings achievable in a realistic scenario would be less than those determined by the model. Caveats include input data accuracy, temperature differential tolerance level, SHS standby power considerations, capital costs and user behaviour to optimise the SHS. All these aspects strongly influence the ultimate savings from the SHS. Thus, there is considerable scope to extend and improve this work. The model can be further tested and refined by using the CAMEL+ HVAC software as a guide to continue building additional layers of sophistication to the existing model to account for additional factors such as psychometrics, external shading factors and beyond. The model could be further enhanced to include additional SHS components for climate control, such as fans and ventilation, integrated with the main air conditioning system to reduce its power demands. Latent heat gains from household equipment, appliances, occupancy and occupant activities can be considered. The concerns on SHS standby power and capital costs should be investigated to determine whether these expenses are sufficiently offset by SHS savings. A lifecycle assessment of SHS is crucial to find net environmental effects of SHS. Finally, the correlation between user behaviour and SHS results is important research to determine the true and optimised potential of SHS energy savings.

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6. References

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